December 2006

WHRP GEOTECHNICS REQUEST FOR PROPOSAL

I. PROBLEM TITLE

Determination of Resilient Modulus Values for Typical Plastic Soils of Wisconsin

II. BACKGROUND AND PROBLEM STATEMENT

The Wisconsin Department of Transportation (WisDOT) is in the process of implementing Mechanistic/Empirical (M/E) procedures and methods for pavement design. One of the major factors in the M/E approach is the inclusion of the resilient modulus of the subgrade soils. WisDOT has not used resilient modulus values for past pavement designs and, as a result, does not have sufficient data or experience to supply these values for Wisconsin soils. WisDOT also does not have the resources available to enter into project specific testing.

After review of the available options, it was determined that the best course of action for WisDOT was to develop methods to provide correlative values (Level 2) for M/E design inputs. This is the intermediate level between using default values based on general soils types and conducting specific testing to determine values for each project. By identifying a limited number of key soils representative of the full spectrum of soils found in Wisconsin, and then subjecting these soils to extensive testing, a base of resilient modulus values could be developed that WisDOT could use to provide correlative values for other similar soils. WisDOT concluded that it did not have the resources necessary to conduct a study of this depth. The effort was then directed to the Wisconsin Highway Research Program (WHRP). This group developed a research project and a proposal submitted by Dr. Hani H. Titi of the University of Wisconsin-Milwaukee was accepted and identified as WHRP Project ID 0092-03-11.

This earlier research proposal called for WisDOT to select 12 to 18 soils that would represent all of the basic soils types found in Wisconsin and supply Dr. Titi with materials for testing. Dr. Titi proposed conducting extensive testing on these materials to determine normal soil parameters such as gradation, hydrometer analysis, Atterberg Limits, maximum density, and optimum moisture. He also proposed testing to determine actual resilient modulus values for these soils under a range of density and moisture conditions. As a final step, he proposed analyzing the accumulated data to determine possible methods to predict resilient modulus values from the more readily available normal soil parameters.

Dr. Titi issued a final report for the project entitled “Determination of Typical Resilient Modulus Values for Selected Soils in Wisconsin” in May 2006. The report provided extensive data on resilient modulus values for the 15 submitted soils over a range of moisture and density conditions. The report also provided extensive data on a full range of more typical soil parameters for the selected soils. Using these typical soils’ parameters, Dr. Titi then attempted to conduct analyses to determine if correlations could be found between certain parameters and the actual resilient modulus values. His analyses found that accurate correlations could not be found if the 15 soils were considered as a whole. This related back to the condition that the 15 soils covered a full range of textures and levels of plasticity. Dr. Titi did find that if the tested soils were divided into groups with similar properties, correlations could be developed. His analyses put the tested soils into the following three groups.

1) Coarse grained, non-plastic soils. (<50% P200, NP)

2) Coarse grained, plastic soils (<50% P200, PI >0)

3) Fine grained soils (>50% P200, PI>0)

However, in subdividing the 15 selected soils into the three groups above, the number of soils within each group became small. Employing extensive regression analyses, Dr. Titi developed empirical formulas for each of the three soil groupings for the factors k_1, k_2, and k_3 necessary to calculate estimated resilient modulus values. Although the formulas where developed for soils within the boundaries of the defined groups, Dr. Titi cautioned that applying the equations to materials with parameters beyond those of specific soils tested had not be validated.

WisDOT has conducted further analyses to test the validity of Dr. Titi’s formulas over a wide range of conditions for each of the identified soil groups. It was found that for the coarse grained, non-plastic soils (Group 1), the formulas gave reasonable results for the normal range of conditions anticipated for this group. However, when analyzing the coarse grained, plastic soils (Group 2) and the fine grained soils (Group 3), it was found that the predicted resilient modulus values became increasingly questionable as the formula/soil parameters increasingly varied from those of the specific soils tested in these groups. This is thought to relate directly back to the small number of soils available for testing and analyses within each of these groups. It is the conclusion of WisDOT that while the predictive formulas for Groups 2 and 3 are valid for the narrow range of soils’ conditions tested and analyzed, these formulas are not valid for the broader range of soil conditions typical for these groups. It was also concluded that additional testing of a broader spectrum of soils was necessary to refine and improve the predictive formulas.

III. SCOPE

This study can be separated into three phases. In the first phase, the researcher must thoroughly review the final report for Project ID 0092-03-11 to understand the procedures, analyses methods, and conclusions of that report. The Department will also present results of our analyses on other soil conditions not specifically tested in the earlier project. In the second phase, the researcher and WisDOT must determine the number and types of soils necessary for further testing and analyses to supplement the original work and analyses. WisDOT would take the responsibility to obtain the identified materials and deliver samples of appropriate volume to the researcher. It is anticipated that approximately 12 soil types will be supplied to the researcher. In the third phase, the researcher would conduct testing using the same methods and procedures as were employed in Project ID 0092-03-11 to determine resilient modulus values and other soil parameter values for the supplemental soils. In the fourth phase, the researcher would conduct necessary regression analyses to expand or modify the predictive equations offered by the original report. All data, findings and conclusions would be presented in a final report.

IV. SPECIFIC RESULTS, FINDINGS, TOOLS, ETC.

This research effort will produce needed supplemental information to expand and refine the empirical equations presented in the final report for Project ID 0092-03-11 to estimate the resilient modulus values of various Wisconsin soils. The study will identify the range of soils needed for further testing and will develop supplemental data for these soils. Through regression analyses, the study will produce refined empirical equations for predicting resilient modulus values. This will provide WisDOT with Level 2 resilient modulus values for soils, which are key components necessary for the implementation of M/E pavement design on WisDOT projects. A final report will be required documenting all research findings and conclusions.

V. LENGTH OF RESEARCH PROJECT AND APPROXIMATE COST

It is estimated that that the time required for this project should not exceed 18 months. The estimated cost should range between $40,000 and $50,000. Time and cost estimates supplied in the research proposals will be evaluated by the TOC as part of the selection criteria.

VI. URGENCY AND POTENTIAL BENEFITS

WisDOT is moving toward implementation of M/E design for pavements and has committed significant time and resources towards this effort. Soil resilient modulus values are a key component in the M/E design process. To achieve accurate and efficient pavement designs, it is essential that the strength contribution of the subgrade soils must be accurately determined. Without this study, WisDOT would be forced to use very conservative general values for soils input. This would significantly diminish the effectiveness and benefits on M/E pavement design.

VII. ADDITIONAL REQUIREMENTS FOR IMPLEMENTATION

The results of the study will produce a valid method to predict soil resilient modulus values by correlation with other common soil parameters. Any changes from current practices will need to be incorporated into the WisDOT Facilities Development manual and pavement design policies. This work is beyond the scope of this research effort.

WHRP_ResilMod.doc

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Transportation Literature Search

Determination of Resilient Modulus of Soils

Prepared for
Wisconsin Highway Research Program
Geotechnics Technical Oversight Committee

January 29, 2007

Transportation Literature Searches are prepared for WisDOT staff and principal investigators to heighten awareness of completed research in areas of current interest. The citations below are representative, rather than exhaustive, of available English-language studies on the topic. Primary online resources for the literature searches are OCLC's WorldCat and TLCat, U.S. DOT's TRIS Online, the National Transportation Library (NTL), TRB's Research in Progress (RiP) and other academic, engineering and scientific databases as appropriate. Links to online copies of cited literature are noted when available. Hard copies may be obtained through the WisDOT Library at library@dot.state.wi.us or 608-264-8142.

SUMMARY
In our search of the above databases we found 25 reports, books and articles pertaining to testing and determining resilient modulus values of selected soils. Of these, 11 were published by or in cooperation with federal transportation agencies, seven by state transportation agencies or institutions, and six in academic journals or conference proceedings. Another report was an M.S. thesis from the University of Missouri-Rolla. Of the federally published reports, three were co-published with state transportation agencies—two with Mississippi and one with New Jersey. With these two states and the documents published by states alone, work from Arkansas, Connecticut (for the New England region), Florida, Kentucky, Minnesota, Mississippi, New Jersey and Wisconsin has been published on determining resilient modulus of soils.

Seven of the studies were published in 2006, eight in 2004, four in 2002, three in 2000, and one each in 2005, 2003 and 2001. We also found two **Research in Progress** projects from Arkansas. These studies seem the likely source of two of the published documents cited below.

KEYWORDS
Resilient, modulus, soils, test.

CITATIONS

Title: Determination of Typical Resilient Modulus Values for Selected Soils in Wisconsin
Author(s): Hani H. Titi, Mohammed B. Elias, Sam Helwany
Date: May 2006
Doc ID/URL: WHRP 0092-03-11, Final Report. http://www.whrp.org/Research/Geotechnics/geo_0092-03-11/WHRP%2003-11%20Determination%20of%20Typical%20Resilient%20Modulus%20Values%20for%20Selected%20Soils%20in%20Wisconsin.pdf
Description: 10 pp.
Contents: The objective of this research is to develop correlations for estimating the resilient modulus of various Wisconsin subgrade soils from basic soil properties. Laboratory testing program was conducted on common subgrade soils to evaluate their physical and compaction properties. The resilient modulus of the investigated soils was determined from the repeated load triaxial test following the AASHTO T 307 procedure. The laboratory testing program produced a high quality and consistent test results database. The high quality test results were assured through a repeatability study and also by performing two tests on each soil specimen at the specified physical conditions. The resilient modulus constitutive equation adopted by NCHRP Project 1-37A was selected for this study. Comprehensive statistical analysis was performed to develop correlations between basic soil properties and the resilient modulus model parameters *ki*. The analysis did not yield good results when the whole test database was used. However, good results were obtained when fine-grained and coarse-grained soils were analyzed separately. The correlations developed in this study were able to estimate the resilient modulus of the compacted subgrade soils

with reasonable accuracy. In order to inspect the performance of the models developed in this study, comparison with the models developed based on LTPP database was made. The LTPP models did not yield good results compared to the models proposed by this study. This is due to differences in the test procedures, test equipment, sample preparation, and other conditions involved with development of both LTPP and the models of this study.

Title: Establish subgrade support values for typical soils in New England
Author(s): Ramesh B. Malla, Shraddha Joshi
Date: April 2006
Doc ID/URL: NETCR 57; NETC Project No. 02-3, Final Report.
Description: 158 pp.
Contents: The main objective of this research project was to establish prediction models for subgrade support (resilient modulus, M sub R) values for typical soils in New England. This soil strength property can be measured in the laboratory by means of repeated load triaxial tests. Nondestructive tests like Falling Weight Deflectometer (FWD) can be used to estimate the modulus value using the backcalculation process. The current study used data extracted from the Long Term Pavement Performance Information Management System (LTPP IMS) Database for 300 test specimens from 19 states in New England and nearby regions in the U.S. and 2 provinces in Canada. Prediction equations were developed using SAS® for six AASHTO soil types, viz. A-1-b, A-3, A-2-4, A-4, A-6, and A-7-6, and Unified Soil Classification Systems (USCS) soil types Coarse Grained Soils and Fine Grained Soils found in the New England region to estimate M sub R. To verify the prediction models, M sub R values for 5 types of soils in New England were determined from laboratory testing using AASHTO standards. The predicted and laboratory measured M sub R values matched reasonably well for the soils considered. Also an attempt was made to obtain the relationship between laboratory M sub R values and the FWD backcalculated modulus from the LTPP test data. No definitive conclusion could be drawn from the analysis. However, in general, FWD backcalculated modulus values were observed to be greater than the laboratory determined modulus values for the same soil type.

Title: Development of Testing Protocol and Correlations for Resilient Modulus of Subgrade Soils
Author(s): Dennis D. Norman, Kyle A. Bennett
Date: 2006
Doc ID/URL: Arkansas State Highway and Transportation Department: Little Rock, Ark., 2006.
Description: 235 pp.; CD-ROM
Contents: This study provides both a description of the theoretical aspects of Spectral Analysis of Surface Waves (SASW) method for determining the thickness and resilient moduli of pavement systems, and presents the results of testing performed using an SASW system assembled as part of this research.

Title: Evaluation of resilient modulus model parameters for mechanistic-empirical pavement design
Author(s): Mohammed B. Elias, Hani H. Titi
Date: 2006
Doc ID/URL: *Transportation Research Record 1967*, 2006: 89-100.
Description: 12 pp.
Contents: Correlations were developed to estimate the resilient modulus of various Wisconsin subgrade soils from basic soil properties. A laboratory testing program was conducted on common subgrade soils to evaluate their physical and compaction properties. The resilient modulus of the investigated soils was determined from repeated load triaxial testing according to the AASHTO T 307 procedure. The laboratory testing program produced consistent results and a high-quality database. The resilient modulus constitutive equation adopted by NCHRP Project 1-37A was selected for this study. Comprehensive statistical analysis was performed to develop correlations between basic soil properties and the resilient modulus model parameters k sub i. The analysis did not yield good results when the whole test database was used. However, good results were obtained when fine-grained and coarse-grained soils were analyzed separately. The correlations developed were able to estimate the resilient modulus of the compacted subgrade soils with reasonable accuracy. To inspect the performance of the models developed in this study, comparison with the models developed on the basis of the Long-Term Pavement Performance (LTPP) database was made. The LTPP models did not yield good results compared with the models proposed by this study because of differences in the test procedures, test equipment, sample preparation, and other conditions involved with development of both LTPP and the models of this study.

Title: Resilient modulus estimation system for fine-grained soils
Author(s): Yuh-Puu Han, Thomas M. Petry, David N. Richardson
Date: 2006
Doc ID/URL: *Transportation Research Record 1967*, 2006: 69-77.
Description: 9 pp.

Contents: A software tool was developed to estimate the resilient modulus of fine-grained subgrade soils. The subgrade resilient modulus is a key factor for use in mechanistic–empirical pavement design methods. However, for routine design use, the test method is too expensive and difficult to perform. Resilient modulus estimation software was developed with expert system approaches. Information entered by the user is first examined for reasonableness and accuracy. Then, data searching processes are initiated, and more than 30 estimation models can be invoked, depending on the availability of input data. All results were evaluated on the basis of certainty rules, such as how well data meet limitations existing during the model's original development environment. The user is given four alternate methods on which to base the choice of a resilient modulus that is most appropriate for the site: one based on certainty rules and three based on statistical methods.

Title: Evaluation of subgrade resilient modulus predictive model for use in mechanistic-empirical pavement design guide
Author(s): Lev Khazanovich, Clara Celauro, Bruce Chadbourn, John Zollars, Shongtao Dai
Date: 2006
Doc ID/URL: *Transportation Research Record 1947*, 2006: 155-166.
Description: 12 pp.
Contents: The characterization of unbound materials in the mechanistic–empirical pavement design guide (MEPDG), also known as the 2002 design guide, is reviewed, and this characterization is applied to Minnesota subgrades. The main emphasis is on the collection of k sub 1, k sub 2, and k sub 3 parameters for Minnesota fine-grained soils and the procedure for the interpretation of the resilient modulus test to provide an input to the multilayer elastic theory (MLET) analysis (Level 2 input). This is an important aspect of adaptation of the MEPDG, because the guide recommends measurement of resilient moduli from laboratory testing, but the procedure does not specify how to interpret the test data to obtain an input for an MLET analysis. The resilient modulus test results from 23 samples collected from several Minnesota locations were used to provide information for the nonlinear finite element program and multilayer elastic theory program. The obtained elastic moduli were compared with the MEPDG recommended ranges for subgrade modulus of elasticity based on the soil classification (Level 3 inputs). The MEPDG Level 3 ranges were found to be reasonable.

Title: An alternative test for the resilient modulus of fine grained subgrades
Author(s): Jonathan M. Smolen, Eric C. Drumm, Kenneth G. Thomas
Date: 2006
Doc ID/URL: *Pavement Mechanics and Performance—GeoShanghai International Conference*, 2006: 271-178.
Description: 8 pp.
Contents: For mechanistic design of pavement systems based on elastic theory, the resilient modulus is used to characterize the soil subgrade. The standard procedure for obtaining resilient modulus is a repeated load triaxial test under a range of stress states. This test is complicated and expensive, and as a result many commercial laboratories will not conduct these tests but instead rely on empirical relationships. An alternative test method was developed in which a hammer of known mass falls onto a volume of soil, and the acceleration response of the falling weight is used to calculate the modulus. While this approach has been used by others, the device described here is new and tests fine-grained soil in an unconfined state. The alternative test method was used on 4 different soils and the results compared with results obtained from the standard repeated load test. The alternative test produced reasonably consistent results and appears to measure a material response that correlates well with the standard triaxial resilient modulus test results. The device was also used to demonstrate the decrease in modulus with increasing water content. It is suggested that the alternative test for resilient modulus may be a cost-effective approximation for mechanistic pavement design for projects where the complete standard test is not warranted.

Title: Development of Testing Protocol and Correlations for Resilient Modulus of Subgrade Soils
Author(s): Norman D. Dennis, Jr., Kyle A. Bennett
Date: January 2005
Doc ID/URL: MBTC (Mack-Blackwell Transportation Center)—2032, Final Report.
Description: 247 pp.
Contents: This study provides a description of the theoretical aspects of Spectral Analysis of Surface Waves (SASW) method for determining the thickness and resilient moduli of pavement systems, and presents the results of testing performed using an SASW system assembled as part of this research. The SASW method is based on the dispersive behavior of surface waves in a layered medium. Dispersion is the term used to describe the fact that the rate at which seismic surface waves (Rayleigh waves) travel through a medium depends upon the frequency of the waves, and this dependency can be used to determine mechanical properties of the medium through which the waves travel. Plotting Rayleigh wave velocity versus frequency (or wavelength) produces a graph called a dispersion curve. This dispersion curve can be used to develop a modulus versus depth profile through the use of a backcalculation

procedure. Once the modulus versus depth profile is known, the resilient modulus and thickness of individual layers can be directly obtained. The results obtained from SASW testing at ten flexible pavement sites throughout the state of Arkansas are presented as part of this report. The thickness and resilient modulus of each layer of each pavement section are estimated from the SASW data using two methods of analysis; simple inversion, and software provided by the University of Texas at El Paso. The thickness results obtained from SASW analyses are compared to known thicknesses measured from cores taken at each of the test sites. The resilient moduli predicted by SASW analysis are compared to the resilient moduli predicted by laboratory resilient modulus testing, to the resilient moduli predicted by Falling Weight Deflectometer (FWD) analysis, and to Standard Penetration test N-values. The simple inversion procedure provided the most consistent results for SASW testing. SASW methods proved to be very accurate in predicting the thickness of various layers in a pavement system and correlated well with the results from laboratory resilient modulus testing.

Title: Prediction of Resilient Modulus from Soil Index Properties
Author(s): K.P. George
Date: November 2004
Doc ID/URL: FHWA/MS-DOT-RD-04-172, Final Report. http://www.mdot.state.ms.us/research/pdf/ResMod.pdf
Description: 72 pp.
Contents: Soil characterization in terms of Resilient Modulus (M sub R) has become crucial for pavement design. For a new design, M sub R values are generally obtained by conducting repeated load triaxial tests on reconstituted/undisturbed cylindrical specimens. Because the test is complex and time-consuming, in-situ tests would be desirable if reliable correlation equations could be established. Alternately, M sub R can be obtained from correlation equations involving stress state and soil physical properties. Several empirical equations have been suggested to estimate M sub R. The main focus of this study is to substantiate the predictability of the existing equations and evaluate the feasibility of using one or more of those equations in predicting the M sub R of Mississippi soils. This study also documents different soil index properties that influence M sub R. Correlation equations developed by the Long Term Pavement Performance (LTPP) program, Minnesota Road Research Project, Georgia DOT, Carmichael and Stuart Drumm et al., Wyoming DOT, and Mississippi DOT are studied/analyzed in detail. Eight road (subgrade) sections from different districts are selected and soils tested (TP 46 Protocol) for M sub R in the laboratory. Other routine laboratory tests are conducted to determine physical properties of the soil. Validity of the correlation equations are addressed by comparing measured M sub R to predicted M sub R. In addition, variations expected in the predicted M sub R due to inherent variability in soil properties is studied by the method of point estimates. The results suggest that LTPP equations are suited for purposes of predicting M sub R of Mississippi subgrade soils. For fine-grain soils, even better predictions are realized with the Mississippi equation. A sensitivity study of those equations suggests that the top five soil index properties influencing M sub R include moisture content, degree of saturation, material passing the #200 sieve, plasticity index and density.

Title: Small Strain and Resilient Modulus Testing of Granular Soils
Author(s): Peter Davich, Joseph Labuz, Bojan Guzina, Andrew Drescher
Date: August 2004
Doc ID/URL: MN/RC-2004-39, Final Report. http://www.lrrb.org/pdf/200439.pdf
Description: 117 pp.
Contents: Resilient modulus, shear strength, dielectric permittivity, and shear and compressional wave speed values were determined for 36 soil specimens created from the six soil samples. These values show that the soils had larger stiffnesses at low moisture contents. It was also noted during testing that some non-uniformity was present within the axial displacement measurements; larger levels of non-uniformity were associated with low moisture contents, possibly due to more heterogeneous moisture distributions within these specimens. Lastly, the data collected during this study was used to recommend a relationship between granular materials' small strain modulus and their resilient modulus. This relationship was given in the form of a hyperbolic model that accurately represents the strain-dependent modulus reduction of the base and subgrade materials. This model will enable field instruments that test at small strains to estimate the resilient modulus of soil layers placed during construction.

Title: Resilient Modulus of Kentucky Soils
Author(s): Tommy C. Hopkins, Tony L. Beckham, Charlie Sun, Bixian Ni
Date: June 2004
Doc ID/URL: KTC-01-07/SPR-163-95-1F; KYSPR-107 (Revised Portion). http://www.ktc.uky.edu/Reports/KTC_01_07_SPR163_95_1F.pdf
Description: 72 pp.
Contents: In recent years, the American Association of State Highway and Transportation Officials (AASHTO) has recommended the use of resilient modulus for characterizing highway materials for pavement design. This

recommendation evolved as a result of a trend in pavement design of using mechanistic models, which are based on the theory of elasticity (layered elastic analysis) or linear and nonlinear, finite element and finite difference methods, or a combination of both those theoretical approaches. Although much progress has been made in recent years in developing mathematical, mechanistic pavement design models, results obtained from those models are only as good as the material parameters used in the models. Resilient modulus of the subgrade soil is an important parameter in the mechanistic models and in the 1993 AASHTO pavement design equation. The main goal of this study was to establish a simple and efficient means of predicting the resilient modulus of any given type of Kentucky soil. To accomplish this purpose, 128 tests were performed on several different soil types from various locations in Kentucky. Specimens were remolded to simulate compaction conditions encountered in the field. Tests were performed on soaked and unsoaked specimens so that an assessment could be made of the effect of moisture on resilient modulus values. Vast differences were found between soaked and unsoaked values of resilient modulus. Based on an analysis of the data, a new mathematical model is proposed which relates resilient modulus to any given selected, or calculated, principal stresses in the subgrade. This model improves the means of obtaining best data "fits" between resilient modulus and stresses. Furthermore, if the AASHTO classification and group index are known, then the resilient modulus of the soil can be predicted from the new model for any known stress condition in the subgrade. Multiple regression analysis was used to obtain relationships between resilient modulus and confining stress and deviator stress. No difficulties were encountered in testing "as-compacted" (unsoaked) samples. Values of R-squared of 91% of unsoaked test specimens were greater than, or equal to, 0.87. However, values of R-squared of only 35% of tested, soaked samples exceeded 0.87. Difficulties were encountered in testing soaked specimens. More research is needed to test saturated, or nearly saturated, soil specimens—conditions that often exist in the field. To make the resilient modulus data and the new model readily available to design personnel of the Kentucky Transportation Cabinet, a "windows" computer software application was developed in a client/server environment. This program is embedded in the Kentucky Geotechnical Database, which resides on a Cabinet server in Frankfort, Kentucky. The resilient predictor model and data are readily available to pavement design personnel statewide.

Title: Cyclic triaxial tests on clay subgrades for analytical pavement design
Author(s): Matthew W. Frost, Paul R. Fleming, Christopher D.F. Rogers
Date: May 2004
Doc ID/URL: *Journal of Transportation Engineering*, Vol. 130 (3), May/June 2004: 378-386.
Description: 9 pp.
Contents: To introduce a performance specification, pavement foundations must be designed using analytical methods incorporating the laboratory measured parameters of resilient elastic modulus and resistance to permanent deformation of the subgrade and foundation materials. This paper presents results from a program of repeated load triaxial tests performed on a range of fine-grained subgrades prepared in a number of states to evaluate these parameters for various design conditions. The results highlight several difficulties in measuring small strains on "undisturbed" soils over a large strain range and in predicting and modeling long-term behavior. However, testing at higher strains has shown that the deviator stress at which the cumulative permanent deformation starts to increase significantly, termed the "threshold stress," approximates to 50% of the deviator stress at failure. In addition, the resilient modulus of the soils is shown to approach a low asymptotic value at higher deviator stress. Comparison between elastic and plastic behavior shows that the deviator stress at "threshold" coincides with the stiffness asymptote. Using these correlations a simplified mechanistic design method for pavement foundations is proposed. © ASCE.

Title: Predicting elastic response characteristics of unbound materials and soils
Author(s): Amber Yau, Harold L. Von Quintus
Date: 2004
Doc ID/URL: *Transportation Research Record 1874*, 2004: 47-56.
Description: 10 pp.
Contents: Most state transportation agencies in the United States use the 1986 or 1993 version of the AASHTO design guide. The AASHTO guide for the design of flexible pavements uses the resilient (elastic) modulus as the property for characterizing all pavement materials and soils. However, state agencies do not routinely measure the resilient modulus in the laboratory but instead estimate the value from strength tests or physical properties. Physical property and repeated load resilient modulus tests are being performed on all unbound materials and soils within the Long-Term Pavement Performance (LTPP) program. Other correlation studies have been performed relating physical properties to the k coefficients of the resilient modulus constitutive equation but have been confined to specific soils. The LTPP program includes a diverse range of soils and unbound pavement materials for which the physical properties and resilient modulus are being measured. Thus, statistical analyses were initiated to confirm these relationships and define the accuracy of predicting the elastic response parameters for use in design. Results from these analyses suggest that the correspondence between the physical properties and the elastic parameters of

the resilient modulus constitutive equation was fair to poor. It was also found that sampling technique had an effect on the elastic parameters of some unbound materials and soils. On the basis of the findings, it was recommended that resilient modulus tests be performed to characterize unbound materials and soils accurately for use in design.

Title: Correlation between resilient modulus, moisture variation, and soil suction for subgrade soils
Author(s): Naji N. Khoury, Musharraf M. Zaman
Date: 2004
Doc ID/URL: *Transportation Research Record 1874*, 2004: 99-107.
Description: 9 pp.
Contents: In recent years, interest in determining the influence of moisture changes on the resilient modulus (M_R) of subgrade soils beneath a pavement has increased. This is because the 1993 AASHTO Guide for Design of Pavement Structures recommends using a single M_R value. The design M_R is expected to account for the seasonal variation in subgrade moisture content This study was undertaken to evaluate the variation of M_R with post-compaction moisture content and suction of selected subgrade soils in Oklahoma. A sandy soil (S-Soil) and a clayey soil (C-Soil) were used for laboratory testing. The C-Soil specimens to be subjected to wetting were prepared by a modified compaction method. The proposed method was expected to enhance the flow of water in a specimen during the wetting process. New laboratory procedures for wetting and drying of specimens were also introduced and were used to establish correlations among M_R, moisture variation, and suction. Results indicate that M_R-moisture content relationships for C-Soil exhibit a hysteretic behavior due to wetting and drying. A similar behavior was observed for S-Soil. The C-Soil was more susceptible than the S-Soil to moisture variation, as expected. It was also observed that changes in M_R values and suction were influenced by the initial (compaction) moisture content.

Title: Resilient modulus models for compacted cohesive soils
Author(s): Phillip S.K. Ooi, A. Ricardo Archilla, Kealohi G. Sandefur
Date: 2004
Doc ID/URL: *Transportation Research Record 1874*, 2004: 115-124.
Description: 10 pp.
Contents: Three-parameter models have been used to represent the effects of confining and shear stresses on the value of resilient modulus. A new generation of such models allows better characterization of the variation of resilient modulus at low deviator stress. These models can be extended to incorporate the effects of soil type, soil structure, and the soil physical state (combination of molding water content and dry unit weight) by relating the three parameters to explanatory variables consisting of common soil parameters. A simple methodology was applied to the results of 78 resilient modulus tests on low- and high-plasticity silts from the island of Oahu, Hawaii, to optimize the choice of explanatory variables. Then, the nonlinear ordinary least-squares method was used to estimate the model parameters. The results indicate that the new generation models not only provide a better fit than the older models, but they also provide a reasonable fit to the data that can capture the effects of stress state, soil type, soil structure, and the soil physical state quite effectively.

Title: Prediction of the Resilient Modulus of Unbound Granular Base and Subbase Materials Based on the California Bearing Ration and Other Test Data
Author(s): Steven Michael Lusher
Date: 2004
Doc ID/URL: M.S. Thesis, University of Missouri-Rolla, 2004. (OCLC 58557966)
Description: 362 pp.
Contents: The paper describes methods for predicting the reilient (elastic) modulus of unbound granular base and subbase materials used in flexible pavement construction based on California Bearing Ratio (CBR) and/or other test data. Current pavement design methods employ relationships that estimate the resilient modulus from CBR results. The most commonly referenced of these relationships are limited in that they were developed using roadbed soils with CBR values no larger than approximately 15%. Therefore, it could be helpful if a model were available that would reliably predict the resilient modulus over a wider range of CBR values and be more specific to unbound granular materials. In this study, four different Missouri aggregates were analyzed that are commonly used in pavement base layers. Two of the aggregates were gravels and two were crushed stone.

Title: Relationship between backcalculated and laboratory-measured resilient moduli of unbound materials
Author(s): G.W. Flintsch, I.L. Al-Qadi, Y. Park, T.L. Brandon, A. Appea
Date: 2003
Doc ID/URL: *Transportation Research Record 1849*, 2003: 177-182.
Description: 6 pp.

Contents: The resilient moduli of an unbound granular subbase (used at the Virginia Smart Road) obtained from laboratory testing were compared with those backcalculated from in situ falling weight deflectometer deflection measurements. Testing was performed on the surface of the finished subgrade and granular subbase layer shortly after construction. The structural capacity of the constructed subgrade and the depth to a stiff layer were computed for 12 experimental sections. The in situ resilient modulus of the granular subbase layer (21-B) was then backcalculated from the deflections measured on top of that layer. The backcalculated layer moduli were clearly stress-dependent, showing an exponential behavior with the bulk stress in the center of the layer. Resilient modulus test results of laboratory-compacted specimens confirmed the stress dependence of the subbase material modulus. Three resilient modulus models were fitted to the data. Although all three models showed good coefficients of determination (R-squared > 90%), the K-theta model was selected because of its simplicity. The correlation between field-backcalculated and laboratory-measured resilient moduli was found to be strong. However, when the stress in the middle of the layer was used in the K-theta model, a shift in the resilient modulus, theta, was observed. This finding suggests that a simple shift factor could be used for the range of stress values considered.

Title: Resilient Modulus Testing for Pavement Components
Author(s): Gary N. Durham, W. Allen Marr, William L. DeGroff
Date: 2002
Doc ID/URL: *ASTM Special Technical Publication 1437*. (ASTM International: Salt Lake City, Utah, 2002).
Description: 274 pp.
Contents: The Symposium on Resilient Modulus Testing for Pavement Components was held in Salt Lake City, Utah on 27-28 June 2002. ASTM International Committee D18 on Soil and Rock and Subcommittee D18.09 on Cyclic and Dynamic Properties of Soils served as sponsors.

Title: Design subgrade resilient modulus for Florida subgrade soils
Author(s): Nishantha Bandara, Geoffrey M. Rowe
Date: 2002
Doc ID/URL: *ASTM Special Technical Publication 1437*, 2002: 85-96.
Description: 12 p.
Contents: Many agencies still use empirical correlations developed to determine design subgrade resilient modulus based on California Bearing Ratio (CBR), R-Value or Soil Support Value (SSV) for pavement design projects. These relationships do not consider the stress dependency of the laboratory determined resilient modulus value. Backcalculated subgrade modulus values from Falling Weight Deflectometer (FWD) tests are also used for this purpose. This study was conducted to determine the relationships between laboratory determined subgrade resilient modulus and the results of Lime Rock Bearing Ratio (LBR) and FWD tests for certain Florida subgrade soils. Laboratory resilient modulus values were determined using subgrade soil samples collected from nine pavement sections. The resilient modulus values were computed by considering stress levels under a standard dual wheel in three typical pavement sections. The roadway sections were selected from various locations in Polk County, Florida. FWD tests were conducted along the selected roadways and LBR tests were conducted on bulk subgrade soil samples. Preliminary relationships to determine design subgrade resilient modulus equivalent to AASHTO Road Test subgrade from FWD and LBR tests were developed for considered typical pavement sections.

Title: Resilient modulus—pavement subgrade design value
Author(s): Richard L. Boudreau
Date: 2002
Doc ID/URL: *ASTM Special Technical Publication 1437*, 2002: 224-232.
Description: 9 pp.
Contents: The results from a laboratory test program were interpreted using recognized constitutive model and layered elastic methodology approach. It was found that cohesive and noncohesive subgrade soils were generally nonlinear inelastic materials, thus their stiffness is dependent on the stress conditions. The design value was recommended to be used to calculate pavement thickness requirements for all pavement types under consideration.

Title: Resilient modulus of Minnesota road research project subgrade soil
Author(s): Shongtao Dai, John Zollars
Date: 2002
Doc ID/URL: *Transportation Research Record 1786*, 2002: 20-28.
Description: 29 pp.
Contents: n/a

Title: Alternative method of determining resilient modulus of subgrade soils using a static triaxial test
Author(s): D.S. Kim, G.C. Kweon, K.H. Lee
Date: February 2001
Doc ID/URL: *Canadian Geotechnical Journal*, Vol. 38 (1), February 2001: 107-116.
Description: 10 pp.
Contents: The resilient moduli (M-R) of subgrade and subbase soils are very important properties in the analysis and design of a flexible pavement system. However, difficulties and complexities in performing cyclic M-R testing and the high cost of the testing system have prevented the cyclic M-R test from becoming a routine test. Therefore, the development of an alternative simple and reliable M-R testing technique is essential to the application of the mechanistic design of a flexible pavement system. In this study, an alternative M-R testing technique for subgrade soils was developed using a static triaxial compression (TX) test. For the development of the alternative testing method, the effects of strain amplitude, loading frequency, mean effective stress, and number of loading cycles on the resilient modulus of subgrade soils were fully investigated. Cyclic M-R, static TX, and resonant column - torsional shear tests were performed to evaluate the deformational characteristics. Synthetic specimens of known stiffnesses ranging from those of soft subgrade soils to those of subbase materials were developed, and all of the testing systems used in this study were calibrated. The alternative M-R testing procedures were proposed considering deformational characteristics of subgrade soils. The reliability of the proposed test method was verified by comparing the moduli determined by the proposed alternative M-R testing method with those determined by the standard M-R tests.

Title: Subgrade Characterization for Highway Pavement Design
Author(s): K.P. George, Waheed Uddin
Date: December 2000
Doc ID/URL: FHWA/MS-DOT-RD-00-131, Final Report.
Description: 198 pp.
Contents: Subgrade soil characterization expressed in terms of Resilient Modulus (M sub R) has become crucial for pavement design. For a new design, M sub R values are generally obtained by conducting repeated triaxial tests on reconstituted/undisturbed cylindrical specimens. Because of the complexities encountered with the test, in-situ tests would be desirable, if reliable correlation can be established. In evaluating existing pavements for rehabilitation selection, subgrade characterization is even more complex. The main focus of this study is to determine subgrade M sub R employing a Dynamic Cone Penetrometer (DCP), especially the automated version. In support of the study, side-by-side Falling Weight Deflectometer (FWD) tests are also conducted. Twelve as-built test sections reflecting typical subgrade soil materials of Mississippi are selected and tested with DCP and FWD before and after pavement construction. Undisturbed samples are extracted using a Shelby tube, and tested in repeated triaxial machine for M sub R. Other routine laboratory tests are conducted to determine physical properties of the soil. In analyzing the data, the soils tested are categorized into two groups, fine- and coarse-grain soils. DCP results (DCP index, penetration/blow) from tests conducted directly in the prepared subgrade are employed to develop regression models for laboratory M sub R prediction. The predictability of the model is substantiated by repeating DCP tests at an independent site. Models for in-situ modulus prediction are also developed in the study. Deflection measurements facilitated the calculation of in-situ modulus, for which three programs were used: MODULUS 5, FWDSOIL and UMPED. The MODULUS 5 backcalculated subgrade modulus shows good agreement with the laboratory M sub R. The FWDSOIL backcalculation program predicts subgrade moduli which are slightly lower than the laboratory M sub R. With emplacement of pavement structure (lime treated subgrade, lime fly ash subbase, and several inches of asphalt concrete) atop the subgrade, the subgrade backcalculated moduli are enhanced, coarse-grain soil showing a larger increase than the fine-grain soil. This latter result, namely the enhancement of subgrade moduli, is substantiated employing the data compiled from 20 Long Term Pavement Performance (LTPP) pavement sections in Mississippi. In order to analyze the automated DCP results, a software designated Dynamic Cone Penetrometer ANalysis (DCPAN), has been developed. With the regression equation incorporated in the software, real time laboratory as well as backcalculated subgrade modulus calculations are plausible in the field.

Title: Resilient Modulus Properties of New Jersey Subgrade Soils
Author(s): A. Maher, T. Bennert, N. Gucunski, W.J. Papp
Date: September 2000
Doc ID/URL: FHWA NJ 2000-01, Final Report.
Description: 151 pp.
Contents: To effectively and economically design pavement systems, subgrade response must be evaluated. Understanding the importance of subgrade soil response to various loading conditions, the American Association of State Highway and Transportation Officials (AASHTO) and the Strategic Highway Research Program (SHRP) established and refined a Standard Test Method for Determining the Resilient Modulus of Soils and Aggregate

Materials. Mechanistic design methods for flexible pavements require the specification of subgrade resilient modulus. The resilient modulus is measured under laboratory conditions that should reflect the conditions the subgrades are subjected to in the field. In this study, a laboratory-testing program was developed to determine the resilient modulus of typical New Jersey subgrade soils. A total of eight soils were tested at different molded water contents to determine their sensitivity to moisture content and cyclic stress ratio. Repeated loading or pumping of the pavement system may induce excess pore water pressure within the subgrade layer thereby reducing the resilient modulus, leading to the premature failure of the pavement. A sensitivity analysis was conducted using an elastic layer computer program to demonstrate the effect of subgrade stiffness on the design thickness of the asphalt layer. As expected, the subgrade stiffness has a dramatic effect on the eventual thickness of the asphalt layer. Laboratory results were used to calibrate a statistical model for effectively predicting the resilient modulus of subgrade soils at various moisture contents and stress ratios. This model will prove to be a valuable tool for pavement engineers to effectively and economically design a pavement system.

Title: Field and Laboratory Evaluation of Resilient Modulus Measurements on Florida Pavement Soils—Executive Summary
Author(s): W.V. Ping, Y. Wang, Z. Yang
Date: September 2000
Doc ID/URL: FL/DOT/RMC/0636(F)-4538, WPI 0510636,; State Job 99700-758-119, Executive Summary.
Description: 50 pp.
Contents: This is the executive summary of a report that summarizes a field and laboratory study to evaluate the resilient modulus of Florida pavement soils. The objectives were to conduct field and laboratory experiment programs and to develop the correlation relationships from the test results. Based on all available experimental data, further analysis was performed: a) to develop reliable correlations between laboratory measured resilient modulus and in-situ layer modulus of pavement soils as measured by field plate bearing load test; b) to correlate field plate bearing values and laboratory resilient modulus measurements with Limerock Bearing Ratio (LBR) values and Falling Weight Deflectometer (FWD) test results; and c) to establish correlation between laboratory measured resilient modulus under optimum moisture condition and laboratory measured resilient modulus under in-situ moisture condition. All correlations are presented and recommendations are made based on the research and analysis from experimental results.

RESEARCH IN PROGRESS

Title: Development of Testing Protocol and Correlations for Resilient Modulus of Subgrade Soils
Principal Investigator(s): Norman D. Dennis, Mack-Blackwell Transportation Center, 501-575-2933.
Start Date: 8/8/2002
RIP URL: http://rip.trb.org/browse/dproject.asp?n=9457
Source Organization: Arkansas State Highway and Transportation Department
Contents: Mechanistic design procedures to be specified in the new 2002 AASHTO Design Guide will require some measure of subgrade resilient modulus, (Mr), as part of the design input. Currently, the test specified to measure resilient modulus is defined by AASHTO T-292-91. This test requires very expensive testing equipment and highly trained operators. It also is very time and labor intensive. As a result, laboratory measured values of resilient modulus are rarely used in design, even though the design transfer functions were developed from laboratory data. Instead, many transportation agencies resort to very crude approximations for resilient modulus values. These values are based on soil or aggregate classification schemes with little regard to the affect of environmental factors such as moisture or load on the selected value. A convenient way to measure modulus in the field is with the Falling Weight Deflectometer (FWD) or with the more recently developed surface wave seismic methods, which are much easier to implement than FWD. However, there are some drawbacks to back calculating modulus values using the deflectometer or with seismic methods, the most serious of which is the lack of data to correlate these field derived modulus values to laboratory-measured values for Arkansas subgrade soils. Since the currently specified laboratory resilient modulus test is so onerous to perform it is unlikely that this correlation will ever happen on a large scale. However, if designers had a simplified laboratory measurement tool at their disposal that was repeatable, relatively cheap and easy to perform they might use laboratory measured values of resilient modulus in their designs and be able to correlate these values to field measured values on a large scale. These measured values of resilient modulus could then account for variations in moisture and load that would be encountered in the field. Use of measured data for the soil properties rather than estimates would insure superior pavement designs and, in many cases, would save money in construction costs.

Title: Estimating Subgrade Resilient Modulus for Pavement Design
Principal Investigator(s): Norman D. Dennis, Mack-Blackwell Transportation Center, 501-575-2933.
Start Date: 1/1/2000
RIP URL: http://rip.trb.org/browse/dproject.asp?n=9447
Source Organization: Arkansas State Highway and Transportation Department
Contents: The Arkansas State Highway and Transportation Department (AHTD) designs its pavement structures in accordance with the 1986/1993 American Association of State Highway and Transportation Officials (AASHTO) Guide for the Design of Pavement Structures. These procedures include an evaluation of the support characteristics of a subgrade soil in terms of resilient modulus (MR) and it has been used almost exclusively in design practice over the past 20 years. The resilient modulus parameter is not measured by the AHTD, but rather, it is typically estimated from R-Value test results. This convention was accepted primarily to avoid equipment and labor expenses that would be associated with the resilient modulus test. Previous research sponsored by the AHTD suggests that current pavement designs are conservative and basically no fundamental relationship exists between the R-Value and the MR parameter for subgrade soils. This project aims to improve the resilient modulus prediction method by developing a material model for subgrade soil based on correlation of soil index properties with the resilient modulus parameter. Index properties for soils are measured by tests that are relatively simple, inexpensive, and repeatable, unlike either test to determine the resilient modulus or R-Value. Correlation of index properties to resilient modulus of a soil has the potential to provide a more accurate and cost effective means for estimating the MR parameter used for pavement design. Development and implementation of the proposed methodology and pavement design guidelines will emphasize mechanistically-based design criteria, generate savings in areas including soil testing and material/construction costs, and contribute to improving pavement performance and design life.